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Thickness of Corrosion Layers on Typical Surfaces of Weathering Steel Bridges

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Abstract

Program of experimental atmospheric corrosion tests carried out on weathering steel bridges in the Czech Republic is briefly introduced in this paper. Attention is paid to the evaluation of corrosion processes on load-bearing structures of girder bridges with the roadway above the supports. The article presents selected results of experimental atmospheric corrosion testing aimed at the measurement of corrosion products thicknesses. It results from the tests that corrosion processes on weathering steels bridges are significantly conditioned by position and location of exposed surface within the structure.

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Keywords: Weathering steel; corrosion; steel structures; patina; atmospheric corrosion tests

1. Introduction

Program of experimental atmospheric corrosion tests has been prepared to study how the structural solution affects the development of corrosion products [1]. Selected results of experimental atmospheric corrosion tests carried out on typical surfaces of weathering steel bridges are presented and evaluated in this paper. Corrosion specimens have been installed on typical surfaces of girder bridges with the roadway above the supports. The thickness of corrosion products measured on particular structural elements and the results after one year exposure of corrosion specimens are introduced and statistically evaluated in this paper.

Towards the end of 2015, the corrosion specimens have been installed on 8 bridges with upper deck located in the Czech Republic, see Table 1. The corrosion specimens are installed on the structure in such a way to simulate

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realistic behaviour of the investigated structural element surface, see Fig. 1. Standard specimens used for atmospheric corrosion tests according to ISO 9226 [2] (test panels 100x150 mm with thickness of 1.5 mm) were chosen for this experimental testing. The specimens were made of sheets (steel grade S355J2WP) commonly used for building facades [3]. The backside of the specimens, i.e. the side adjacent to the steel structure, is masked to evaluate the corrosion attack only on the exposed side of the specimen.

Table 1. Weathering steel girder bridges with the roadway above the supports included to the program of experimental testing

Monitored structures	Year of construction	Number of tested surfaces
01 - Road bridge over the river Ostravice in Frydek-Mistek	1986	8
02 - Railway bridge in Prague	1981	8
03 - Road bridge over the railway line on the road II/456 in Ostrava	2008	16
04 - Road bridge over the river Odra on the road II/456 in Ostrava	2008	8
05 - Road bridge over the railway line on the road I/56 in Ostrava	2008	9
06 - Road bridge on Opavska street over the highway D1 in Ostrava	2001	12
07 - Road bridge on Opavska street over the railway line in Ostrava	1983	6
08 – Road bridge over the river Opavice in Opava	2008	9

Fig. 1. Installation of corrosion specimens (road bridge over the river Odra on the road II/456 in Ostrava)

Corrosion specimens are attached to the steel structure using a simple anchoring device made of stainless steel. This attachment method provides tight contact between corrosion specimen and examined surface of the steel structure. The contact area between the pressure element and the corrosion specimen is minimal, so there is no influence in the development of corrosion products on the exposed surface and specimens copy the thermal inertia of structural elements. Three corrosion specimens have been installed on each of the examined surfaces. Before the installation, the thickness of corrosion products had been measured on all investigated surfaces. Portable thickness gauge based on magnetic induction is typically used for the measurement of rust layers thickness. The planned duration of the experimental atmospherics testing is 10 years. The thickness of corrosion products on surface of specimens is measured at yearly intervals. Sampling of corrosion specimens for determination of corrosion losses is planned at 1, 3 and 10 years of exposure (only the corrosion data after one year exposure of specimens are available nowadays).

2. Experimentally measured data after one year of exposure

2.1. Corrosion thicknesses on structural elements

Results of experimentally measured thicknesses of corrosion layers that were developed on typical surfaces of bridges listed in Table 1 are introduced in this chapter. For each surface, a total of 30 measurements were recorded. The ascertained average values of corrosion products thicknesses are stated in Table 2. The results correspond to the surfaces with visually favorable patina development that are not influenced by leakage from failed drainage system [4]. When evaluating the corrosion layers, it is necessary to distinguish between external and internal surfaces and also between horizontal and vertical surfaces. Horizontal surfaces are divided into surfaces exposed from above (upper surface of the bottom flanges) and surfaces exposed from the bottom (soffit areas).

Table 2. Average thicknesses of corrosion products developed on typical surfaces of tested bridges

Surface	Monitored structure (see Table 1)							
	01	02	03	04	05	06	07	08
Average thicknesses of corrosion products developed on typical surfaces of tested bridges (μm) (coefficient of variation V_x is stated in parentheses)								
Outer web of the main girder	76.3 (0.21)	81.8 (0.32)	60.9 (0.25)	59.4 (0.22)	63.7 (0.27)	127.1 (0.36)	90.9 (0.29)	67.4 (0.37)
Outer web of the main girder 50 mm above the bottom flange	101.4 (0.35)	146.0 (0.28)	72.7 (0.40)	79.8 (0.35)	61.4 (0.28)	183.7 (0.30)	-	68.5 (0.33)
Inner web of the main girder	76.9 (0.19)	96.8 (0.38)	77.6 (0.25)	65.7 (0.28)	53.6 (0.29)	110.3 (0.24)	108.9 (0.22)	68.5 (0.27)
Upper outer surface of bottom flange of the main girder	207.0 (0.26)	206.3 (0.19)	149.6 (0.21)	134.8 (0.25)	91.3 (0.25)	272.0 (0.18)	-	120.4 (0.23)
Upper inner surface of bottom flange of the main girder	167.9 (0.22)	234.9 (0.26)	121.1 (0.14)	125.4 (0.25)	91.7 (0.28)	-	-	122.0 (0.23)
Soffit area of upper flange of the main girder	104.5 (0.25)	185.7 (0.23)	113.9 (0.28)	108.2 (0.34)	105.3 (0.25)	134.1 (0.27)	114.2 (0.19)	102.3 (0.23)
Soffit area of bottom flange of the main girder	-	80.1 (0.28)	118.0 (0.30)	73.6 (0.48)	66.7 (0.24)	158.4 (0.31)	168.2 (0.26)	112.8 (0.28)

The bridge structures included in the program of experimental corrosion tests are situated in different locations and the bridges are also of different ages. Direct comparison of thicknesses measured in different environmental conditions is not suitable. For this reason, the relative quantities are used for comparison and evaluation of corrosion processes on typical surfaces of the tested bridges. The outer web of main girders was selected as the reference area. The exposition time of the newly built bridges is 7 years and the corrosion layers are already rather stable, though an additional moderate increase of corrosion thicknesses cannot be excluded during further exposition [5-7].

Average values (m_x) and coefficients of variation (V_x) of the ascertained relative quantities are used for the basic statistical evaluation of experimentally measured data. From practical point of view, it is also suitable to state the border values of expected results, e.g. the quantiles 5% and 95%. Normal distribution of random variable is expected and the quantiles can be calculated using equations given in European standards [8]:

$$x_{0.05} = m_x(1 - k_n V_x) \quad (1)$$

$$x_{0.95} = m_x(1 + k_n V_x) \quad (2)$$

The value of the coefficient k_n depends on the range of data set (k_n = 2.33 for n = 5; k_n = 2.18 for n = 6; k_n = 2.09 for

n = 7; k_n = 2.00 for n = 8).

It results from the values listed in Table 2 that the most bulky corrosion products have been developed on upper outer surfaces of the bottom flanges of main girders. The average thicknesses of corrosion products on bottom flanges are 2.19 times higher compared to the adjacent external surfaces of webs (coefficient of variation of the ratio V_x = 0.19; quantile 5% $x_{0.05}$ = 1.32; quantile 95% $x_{0.95}$ = 3.05). Maximum value x_{max} = 272.0 μm doesn't exceed the admissible value recommended for fully protective patina layers x_{lim} = 400 μm [4].

Average thicknesses of corrosion products on upper surfaces of the inner flanges are smaller compared with external flanges, however the difference between both quantities is small. In relation to the reference outer web of main girder, the average thicknesses of corrosion products are 2.08 times higher (coefficient of variation of the ratio V_x = 0.21; quantile 5% $x_{0.05}$ = 1.13; quantile 95% $x_{0.95}$ = 3.04).

Visually different (darker) strip of corrosion products is usually created on outer webs close to the bottom flanges, see Fig. 2. This phenomenon occurs only on the outer webs and is caused by different type of wetting in contrast to usual web surfaces of the main girders. On the adjacent bottom flange remains more moisture, deposition, dirt and in winter also snow. The average thicknesses of corrosion products measured on outer webs close to the bottom flanges are 1.31 times higher compared to typical surface of the web (coefficient of variation of the ratio V_x = 0.19; quantile 5% $x_{0.05}$ = 0.77; quantile 95% $x_{0.95}$ = 1.84).

Fig. 2. Visually different strip of corrosion products on the outer web of main girder close to the bottom flange.

It follows from the comparison of corrosion processes on the outer and inner webs of main girders that the thicknesses of corrosion products are similar (average value m_x = 1.01 coefficient of variation of the ratio V_x = 0.12; quantile 5% $x_{0.05}$ = 0.84; quantile 95% $x_{0.95}$ = 1.35).

Higher values of patina thicknesses compared to the reference area were identified on soffit surfaces. Average values of patina thicknesses on the soffit surface of upper flanges 1.60 times exceed the average thicknesses measured on reference webs of main girders (coefficient of variation of the ratio V_x = 0.23; quantile 5% $x_{0.05}$ = 0.88; quantile 95% $x_{0.95}$ = 2.33). Lower values of the ratio were obtained for soffit areas of bottom flanges – average corrosion thicknesses are 1.42 times higher compared to the reference webs (coefficient of variation of the ratio V_x = 0.25; quantile 5% $x_{0.05}$ = 0.67; quantile 95% $x_{0.95}$ = 2.18).

2.2. Corrosion thicknesses on specimens

Average thicknesses of corrosion products that have developed on corrosion specimens after one year of exposure (young corrosion products) are stated in Table 3. Corrosion specimens have been fixed on the same surfaces as defined in Section 2.1.

The maximum thickness values of corrosion products were detected on the upper outer surfaces of the bottom flanges of main girders. The average thicknesses of the corrosion products are 2.69 times higher compared to the corrosion thicknesses of the outer web of main girders (coefficient of variation of the ratio $V_x = 0.20$; quantile 5% $x_{0.05} = 1.53$; quantile 95% $x_{0.95} = 3.84$).

Corrosion thicknesses of the patina on upper surfaces of the inner flanges are smaller compared with external flanges. When compared with the reference outer web of the main girder, the average corrosion thicknesses of internal flanges are 2.15 times higher (coefficient of variation of the ratio $V_x = 0.16$; quantile 5% $x_{0.05} = 1.38$; quantile 95% $x_{0.95} = 2.91$).

The average thicknesses of corrosion products measured on outer webs 50 mm above the bottom flanges are 1,15 times higher compared to typical surface of the web (coefficient of variation of the ratio $V_x = 0.10$; quantile 5% $x_{0.05} = 0.88$; quantile 95% $x_{0.95} = 1.42$).

It follows from the comparison of corrosion processes on the outer and inner webs of main girders that the average thicknesses of corrosion products measured on the internal webs are average 0.88 multiple of losses on the outer webs (coefficient of variation of the ratio $V_x = 0.21$; quantile 5% $x_{0.05} = 0.49$; quantile 95% $x_{0.95} = 1.26$).

Average thicknesses of corrosion products on the soffit surface of the upper flange 1.10 times exceed average thicknesses on the outer web of the main girder (coefficient of variation of the ratio $V_x = 0.22$; quantile 5% $x_{0.05} = 0.59$; quantile 95% $x_{0.95} = 1.60$).

Thicknesses of corrosion layers on soffit areas of bottom flanges are slightly higher compared to the values that have been measured on soffit areas of upper flanges. Average thicknesses of corrosion products are 1.24 times higher in comparison with the outer web of the main girder (coefficient of variation of the ratio $V_x = 0.17$; quantile 5% $x_{0.05} = 0.76$; quantile 95% $x_{0.95} = 1.71$).

Table 3. Average thicknesses of corrosion products developed on corrosion specimens after one year of exposure

Surface	Monitored structure (see Table 1)							
	01	02	03	04	05	06	07	08
Average thicknesses of corrosion products developed on corrosion specimens after one year of exposure (μm) (coefficient of variation V_x is stated in parentheses)								
Outer web of the main girder	46.5 (0.19)	25.4 (0.36)	24.8 (0.40)	32.5 (0.45)	19.4 (0.41)	54.4 (0.34)	27.0 (0.41)	-
Outer web of the main girder 50 mm above the bottom flange	51.5 (0.31)	29.1 (0.42)	26.0 (0.42)	35.4 (0.38)	-	74.8 (0.33)	-	-
Inner web of the main girder	41.6 (0.27)	23.7 (0.52)	26.6 (0.43)	36.1 (0.37)	10.5 (0.42)	48.5 (0.19)	19.2 (0.50)	-
Upper outer surface of bottom flange of the main girder	87.5 (0.19)	87.4 (0.36)	76.8 (0.19)	70.4 (0.20)	51.8 (0.34)	156.0 (0.20)	-	-
Upper inner surface of bottom flange of the main girder	66.9 (0.24)	54.1 (0.33)	52.2 (0.22)	77.0 (0.22)	44.2 (0.33)	138.8 (0.17)	-	-
Soffit area of upper flange of the main girder	41.4 (0.25)	39.4 (0.41)	32.5 (0.43)	36.6 (0.27)	16.9 (0.47)	45.6 (0.30)	29.3 (0.40)	-
Soffit area of bottom flange of the main girder	-	31.0 (0.30)	40.7 (0.46)	36.8 (0.32)	18.0 (0.32)	63.9 (0.20)	35.5 (0.30)	-

3. Discussion of results

It follows from the experimentally measured results that the corrosion processes on weathering steel bridges are significantly conditioned by position and location of exposed surface within the structure. Significant differences in thicknesses of corrosion products were found out both on stable patina created on structural elements with long term exposition and on young patina forming on corrosion specimens after one year of exposure, see Table 4.

Most bulky corrosion products have been developed on upper surfaces of bottom flanges of main girders. The results for stable patina and young corrosion products are almost similar - slightly higher values of the ratio between thicknesses on upper surfaces of bottom flanges and external webs were identified for the young patina developed on corrosion specimens after one year of exposure. Upper parts of bottom flanges are the only surfaces where the above mentioned ratio was higher at corrosion specimens.

Increased thicknesses of corrosion products were detected on external webs of main girders close to the bottom flanges. This effect is caused by higher wetting in contrast to typical web surfaces. However, the increase of corrosion thicknesses is not extensive and the protective ability of rust layer is still sufficient. Differences between external and internal webs of main girders are very small.

Higher thicknesses of corrosion products compared to outer webs were identified on soffit areas of main girders. Considerable differences were found out in the calculated ratio of corrosion thicknesses between stable and one young rust layer. Especially for the soffit area of upper flanges, the measured thicknesses of corrosion products after one year of exposure do not correspond to the final corrosion state on the structure.

Table 4. Corrosion states on structural elements (long term exposure) and corrosion specimens (one year exposure)

Surface	Corrosion state *)		
	r_1	r_2	r_1/ r_2
Outer web of the main girder 50 mm above the bottom flange	1.31	1.15	1.14
Inner web of the main girder	1.01	0.88	1.15
Upper outer surface of bottom flange of the main girder	2.19	2.69	0.81
Upper inner surface of bottom flange of the main girder	2.08	2.15	0.97
Soffit area of upper flange of the main girder	1.60	1.10	1.45
Soffit area of bottom flange of the main girder	1.42	1.24	1.14

*) Calculated ratios:

r_1 – stable patina ratio, *i.e.* ratio between the average thickness of corrosion products developed on the evaluated surface related to the average thickness of corrosion products on reference outer web of the main girder

r_2 – young patina ratio, *i.e.* ratio between the average thickness of corrosion products developed on specimens after one year exposure related to the average thickness of corrosion products developed on specimens placed on reference outer web of the main girder

4. Conclusions

The program of experimental atmospheric corrosion tests of weathering steels is designed as a long-term project. Complex results of the program will be first available after 10 years of corrosion specimens' exposure. To create conclusions about the corrosion processes on typical surfaces of steel structures it was necessary to install corrosion specimens on a sufficient number of surfaces. Simple attachment of specimens on evaluated surfaces of the structure can serve as economically inexpensive approach for evaluation of corrosion processes on weathering steel structures. This method allows quantifying the actual corrosion state.

The main objective of the program is specification of analytical prediction model for calculation of design values of corrosion losses [9] on the basis of measured data statistical evaluation. In practice, prediction models for calculation of corrosion losses are used primarily for design of load-bearing structures of buildings. Statically needed value of required corrosion allowances is determined on the basis of predicted corrosion losses [10]. The experimental results can also be used for evaluation of time-dependent structural reliability using probabilistic based methods [11-12].

Measurement of thicknesses of corrosion products can serve as a tool for apposite estimation of corrosion processes on weathering steel bridges. The measurement is very simple - is carried out using a portable thickness gauge without need anyhow interfere into the structure. It results from the measurements that corrosion processes on weathering steel bridges are significantly conditioned by location of exposed surfaces within the structure.

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